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Magnetic modelling of the Umvimeela and East dykes: Evidence for regional tilting of the Zimbabwe craton adjacent to the Limpopo Belt

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Models of the Umvimeela and East dykes of Zimbabwe have been deduced from aeromagnetic data. Assuming a constant magnetic susceptibility and direction of remanent magnetization the models show the two dykes are essentially vertical with a mean dip of 84° towards the Great Dyke for the Umvimeela dyke and 89° away from the Great Dyke for the East dyke (excluding results from south of latitude 20.5°S). There is a large variation in the width of the dykes. A mean width of 204 m for the Umvimeela dyke and 106 m for the East dyke were obtained. The large errors may represent true variations in width or result from variations in the susceptibility. Both dykes have shallower dips south of latitude 20.5 S. The Umvimeela dyke has a mean dip of 70° and the East dyke of 80°. This, together with palaeomagnetic data from the Umvimeela dyke, suggests a tilting of the Zimbabwe craton adjacent to the Limpopo Belt over a zone about 100 km in width. The axis of rotation is roughly parallel to the northern margin of the Limpopo Belt.

The formation of the Archaean Zimbabwe craton (Fig. 1) was the culmination of events during the circa 2 900-2 600 Ma time span (Wilson, 1990). It is bounded to the north by the Pan-African Zambezi Belt, to the east by the Pan-African Mozambique Belt and to the south by the Archaean-Proterozoic Limpopo Belt. The intrusion of the Great Dyke at 2 461 ±16 Ma (Hamilton, 1977) was the first major igneous event after the cratonization. The Dyke is 550 km long and up to 11 km wide and extends in a NNE-trending direction from the Limpopo Belt in the south into the Zambezi Belt in the north. Running nearly parallel to the Dyke for its entire length are its main satellites, the Umvimeela (to the west) and the East dykes. These are composed of quartz gabbro and, on structural and petrological grounds, were correlated with the Great Dyke by Worst (1960). McElhinny and Gough (1963) and Jones *et al.* (1975) confirmed this relationship with their palaeomagnetic results.

The Great Dyke and its satellites are described and analysed by Wilson and Prendergast (1988). The Dyke represents the remains of a series of near contiguous layered igneous bodies which are Y-shaped in cross section passing downwards into a feeder. A gravity survey across the Great Dyke showed that the dunite feeder is not always vertical (Podmore, 1985; Podmore and Wilson, 1987). The satellites are generally undeformed except for relatively small offsets associated with a number of cross cutting faults (Mchingwe Fault set). They are however extensively deformed at the northern end within the Zambezi Belt. The dykes often crop out on the surface but their margins are rarely exposed and only rough estimates of dyke thicknesses and dips have previously been given.

The Limpopo Belt is a major geological feature of southern Africa but its origin and subsequent development are still far from fully understood (Barton, 1983). It is an ENE trending zone lying between the Zimbabwe and the Kaapvaal cratons about 600 km long and ranging in width from 240 to 320 km. Most of the recent models attempting to explain its evolution have invoked continental collision, with rocks of the Kaapvaal craton thrust onto those of the Zimbabwe craton. The Great Dyke terminates

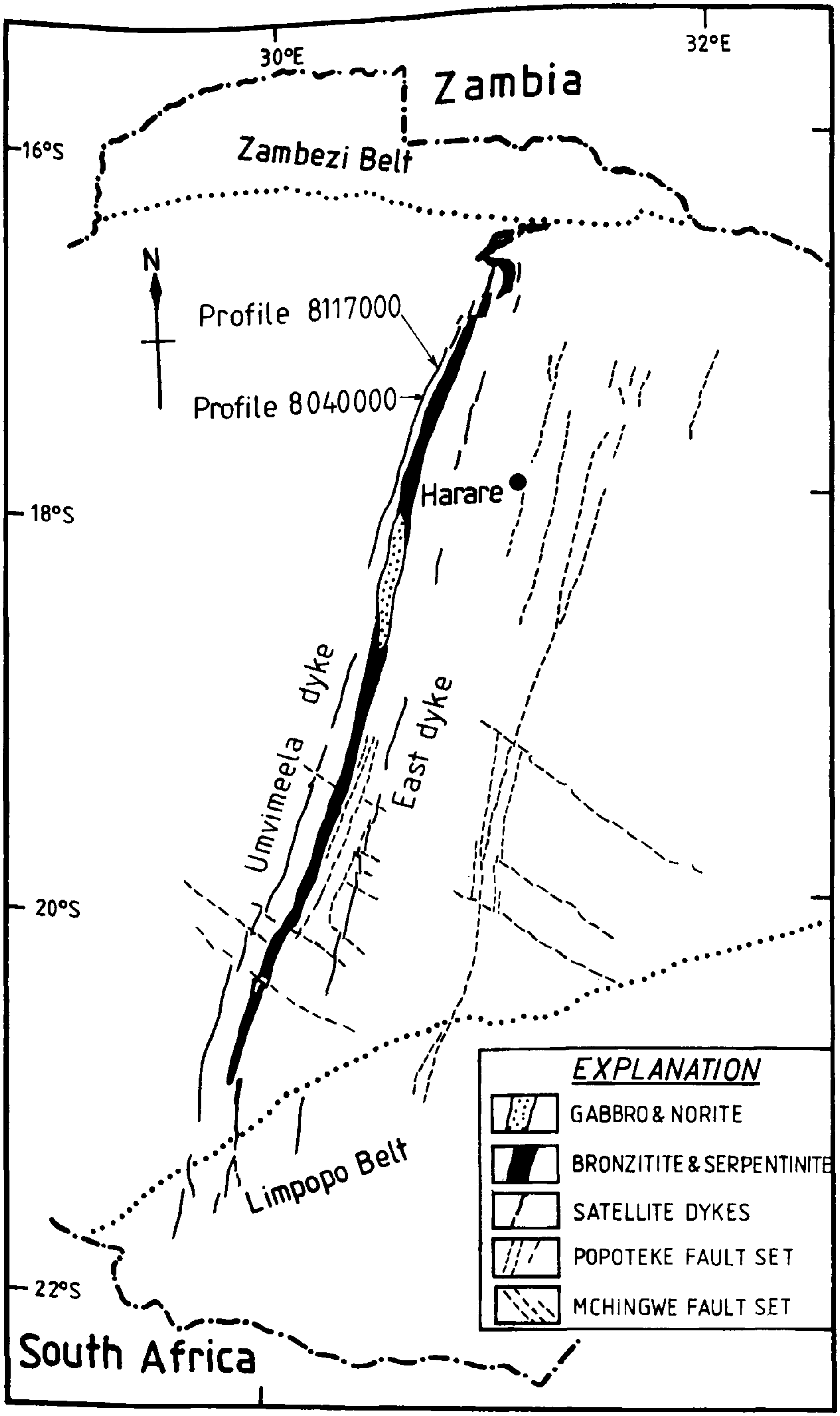


Fig. 1: Simplified map showing the Great Dyke, its satellites, the Popoteke and Mchingwe Fault sets

about 30 km north of the orthopyroxene isograd which is traditionally taken as the northern boundary of the Limpopo Belt. The Dyke does not appear to have been affected by Limpopo Belt tectonics. The southern extensions of the Umvimeela and East dykes and the Main Satellite dyke extend for over 80 km beyond the southern limit of the Great Dyke and cut into the Limpopo Belt. These also appear unaffected by the Limpopo metamorphism. Thus the intrusion of the Great Dyke post-dates any major tectonic event within the Belt. A thermal event within the Belt has been identified from rubidium-strontium mineral ages which peak at 2 000 Ma (Van Breemen and Dodson, 1972) and has also been detected in palaeomagnetic studies (Jones *et al.*, 1975; Morgan and Briden, 1981). This event, which coincided with a major igneous event in the Zimbabwe craton, the Mashonaland Igneous Event (Wilson, 1990) was accompanied by widespread reactivation of the overall Great Dyke fracture pattern with dykes being intruded into some of these fractures (Wilson, 1990).

The present work, which extends that of Podmore and Mushayandebvu (1990), has involved a detailed study of a number of aeromagnetic profiles over the Umvimeela and East dykes.

Magnetic data

The data were collected in the first phase of an aeromagnetic survey programme of Zimbabwe funded by the Canadian International Development Agency in 1983. The survey was carried out at a mean terrain clearance of 305 m with EW traverse lines spaced 1 km apart and NS tie lines every 14 km. Total magnetic field data was obtained using a proton magnetometer with a resolution of 0.25 nT. The flight path was recovered from 35 mm track film and transferred onto aerial photographs. The paths were further transferred to topographic maps and digitized. The Doppler system was used to aid in navigation. The data used in this study were made available by the Geological Survey of Zimbabwe in grid form (125 m grid spacing), together with the accompanying aeromagnetic geophysical series maps. The data were not pole reduced and the IGRF had not been removed. Profiles, about 8 km long, were selected from the grids using the Geosoft™ geophysical package. This normally entailed identifying a suitable location from the aeromagnetic maps and then reading off the UTM coordinates of the start of the profile. The aeromagnetic maps show the flight lines and profiles close to flight lines were generally chosen in order to reduce errors introduced by digitizing and interpolating between flight lines. Seventy one profiles were extracted for the Umvimeela dyke and thirteen for the East dyke.

Magnetic modelling

Geosoft MAGMOD-3™ was used to model the profiles. The models used assumed a 2-dimensional tabular body extending to infinity laterally and to a great depth. A mean initial susceptibility for the dyke (expressed in cgs emu for Geosoft™) of 6.5×10^{-4} (Mushayandebvu, 1991) was used and held constant during the modelling. The strike of the dyke is around 10° with the profiles running EW. MAGMOD-3™ projects the readings onto a profile perpendicular to the dyke. The remanent magnetization of the Umvimeela dyke is D = 219.8°, I = -58.7° and a_{95} = 3.3° (Mushayandebvu, 1991). The remanent magnetization of the East dyke is D = 204.6°, I = -56.2° and a_{95} = 9.2° (Mushayandebvu, 1991). The geomagnetic field was taken to have an inclination of -55° and a declination of -10°. The Geosoft program allows for a regional field to be removed from the profiles and this was estimated by choosing a profile much longer than is necessary to cover the dyke.

Remanent magnetization, often a complication in magnetic interpretation, is here a very significant factor. For the Umvimeela and East dykes, the component of the remanence direction in the plane perpendicular to the dyke is very close to that of the present geomagnetic field. Hence the anomaly could be modelled as either fully remanent or fully induced. If the magnetization is assumed to be induced then very high susceptibility values around 0.1 emu are required to produce the observed anomalies. But with the susceptibility fixed the contribution of the remanent magnetization is more significant as shown by the ratio of the remanence to the induced magnetisation, the remanence ratio, in Tables 1 and 2. Two profiles with their modelled results are given in Fig. 2.

Results from the Umvimeela and East dykes

The results from the Umvimeela dyke are presented in Table 1. Location of the profiles is given in UTM coordinates and the profiles run EW. The Geosoft™ notation used to represent the dips gives a dip of zero for a horizontal dyke extending to the east and a dip of 180° if it is extending to the west. The topographic maps which cover the profiles are listed. The results give an average width for the dyke of 204 m with a large standard deviation of 130 m. The large uncertainty could represent actual variations in the width of the dyke or variations in the magnetic susceptibility. An average dip of 80.6° towards the Great Dyke was obtained. This has a standard deviation of 13.6° with a standard error in the mean of 1.6°. This gives a 95% confidence interval for the mean of 79.0° to 82.2°. Strictly speaking one should not be using normal statistics since the dip is a vector, but this was carried out as a first approximation, bearing in mind that the dyke does not vary much in its strike direction. It has also been noted that each model gives a best fit value for the main parameters (i.e. dip, width, remanence ratio) under the assumptions of the 2-dimensional tabular model. Things might be different with different assumptions. It is therefore not surprising that there is a lot of scatter in dip and width. As a result it is felt that these statistics should not be given any rigorous statistical treatment with only the means and the graphical presentation being used. An average ratio of remanent to induced magnetization of 20 was obtained. Fig. 3 (a) shows the way the dip of the dyke varies over its length and it shows the large scatter of the dip. Points south of coordinate UTM 7 800 000 (which roughly coincides with latitude 20.5°S) have been plotted with a different symbol. Even with the large scatter in the points it is obvious that there is a change in the mean of the dips at this point. The mean to the north is 83.9° while to the south it is 70.1° giving a difference of 13.8° between the two means.

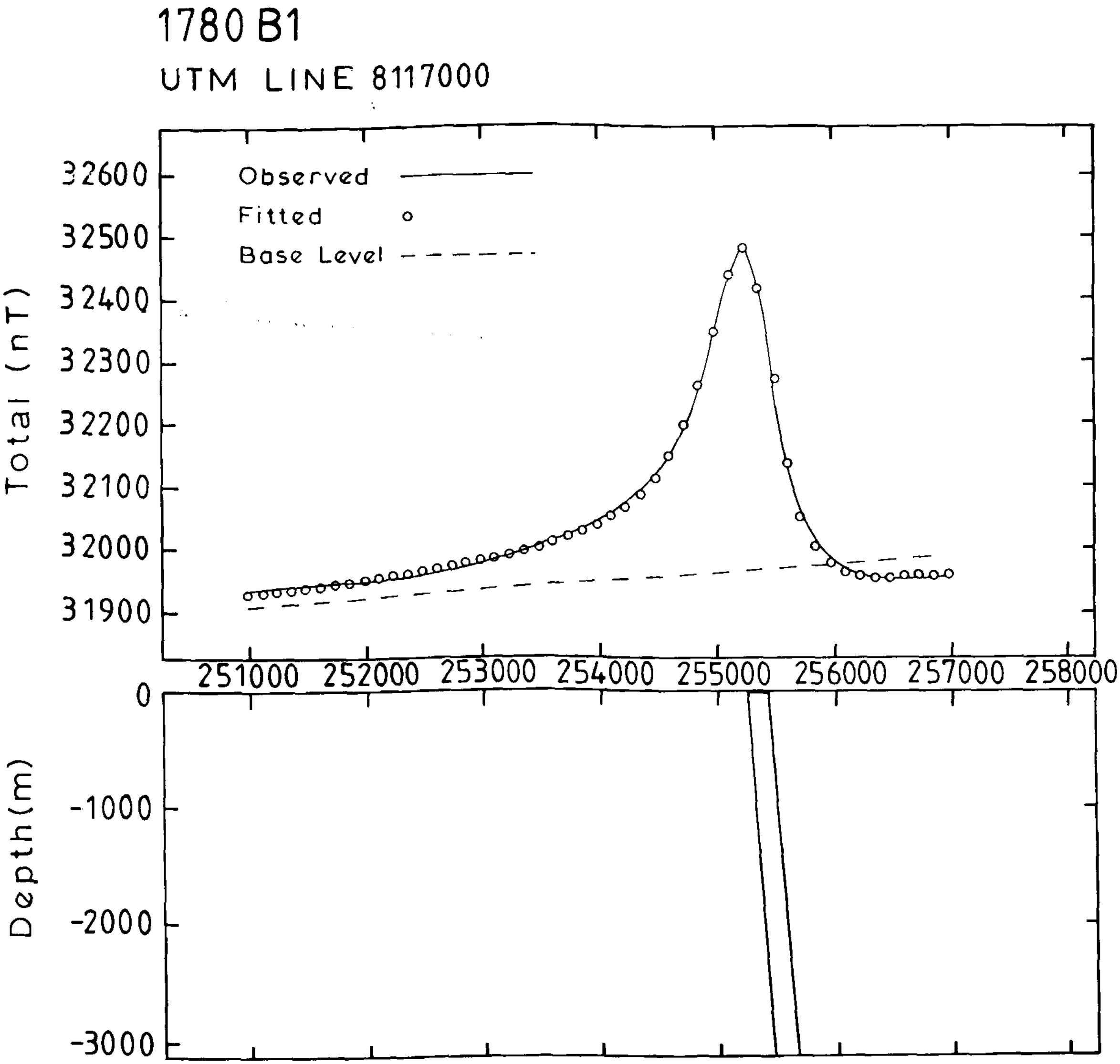
The results from the East dyke (Table 2) give an average thickness for the dyke of 106 m. An average dip of 84.5° away from the Great Dyke was obtained with an average ratio of remanent to induced magnetization of 11. Fig. 3 (b) shows the variation of the dips with location. Dips at points south of UTM coordinate 7 800 000, when compared to those to the north, show a similar difference to that observed with the Umvimeela dyke. The mean to the north is 89.0° and to the south it is 80.4°

Rotation of the southern section of the Great Dyke

The results have shown that there is a systematic difference between the dips of the Umvimeela and East dykes north and south of the UTM coordinate 7 800 000. This difference could be explained as being due to a difference in altitude at the time of emplacement of both dykes, or as representing a rotation of the southern section relative to north, after emplacement. Palaeomagnetic results from the Umvimeela dyke (Mushayandebvu, 1990) have been used in an attempt to resolve this question. Figs. 4 (a) and 4(b) show the variation of the declination and inclination of the primary magnetization of the Umvimeela dyke. Three sites at its southern end suggest a change in the remanent magnetization with both the declination and inclination having higher values than in general. The mean of the directions of magnetization to the north of latitude 20.5° S is D = 217.0° and I = -57.6° and that for the south is D = 232.2° and I = -62.6° with the angle between the means being 9° The mean directions are now labelled P_N and P_S respectively. If a single rotation of the

Table 1: Characteristics of the magnetic models of Umvimeela Dyke

Topographic Map No.	UTM LIne No. x103	Depth to Top (m)	Thickness (m)	Remanance Ratio	Dip
1730B1	8118	64.8	164.0	26.5	87
	8117	13.6	196.2	29.1	85
	8116	268.0	200.0	29.4	75
	8108	72.8	324.0	39.2	79
	8104	182.0	236.0	29.5	86
	8102	43.0	218.0	39.4	87
	8099	168.0	175.0	40.1	101
	8096	166.0	358.0	17.4	90
1730B3	8089	192.0	326.0	29.9	82
	8088	42.1	160.6	53.0	71
	8085	239.0	368.0	34.9	66
	8083	314.0	430.0	10.1	85
	8082	83.7	169.8	24.3	84
	8080	43.0	182.6	20.4	86
	8077	68.1	64.2	31.0	82
	8076	110.0	74.0	34.8	82
	8066	112.0	125.8	42.5	78
	8065	195.0	306.0	21.4	76
1730C2	8056	185.0	186.6	27.5	97
	8055	3.8	184.6	16.2	100
	8051	196.0	394.0	6.7	95
	8042	167.0	90.0	34.6	105
	8040	28.7	172.0	18.6	91
	8038	19.1	360.0	10.8	80
1730C4	8034	199.0	62.8	28.4	71
	8033	68.7	60.6	28.6	82
	8029	197.0	346.0	5.1	75
1830C3	7919	199.9	250.0	13.2	61
	7918	198.9	199.0	13.6	72
	7917	160.0	104.0	35.2	76
	7910	4.8	45.2	21.2	100
	7903	196.0	212.0	11.6	101
	7901	198.0	178.8	11.7	86
	7898	156.0	190.6	19.6	86
1930A1	7896	197.0	79.6	33.7	98
	7890	200.0	164.4	12.0	69
	7889	194.0	84.0	37.1	68
	7888	329.0	368.0	9.7	71
	7885	26.7	188.0	12.1	67
	7883	212.0	123.8	19.2	78
	7882	42.1	212.0	10.4	74
1930A3	7868	234.0	68.6	15.7	79
	7867	80.9	86.8	4.6	72
	7864	413.0	39.0	11.3	74
1929B4	7850	113.0	442.0	8.1	83
	7847	231.0	580.0	4.5	103
	7845	172.0	296.0	7.7	89
1929D2	7841	252.0	126.6	24.9	76
	7839	2.0	542.0	3.5	83
	7832	201.0	168.4	23.7	77
1929D4	7812	8.7	80.8	27.2	115
	7811	202.0	262.0	12.8	119
	7806	114.0	74.0	13.3	98
	7803	184.0	124.2	13.2	80
	7802	104.0	104.8	11.3	55
2029B1	7776	141.0	123.8	15.9	82
	7775	130.0	372.0	4.5	69
2029B3	7753	112.0	178.4	8.9	83
	7752	3.5	320.0	17.7	65
	7751	165.0	80.8	13.5	57
2029D1	7718	384.0	292.0	19.4	59
	7717	402.0	134.4	44.3	60
	7716	279.0	99.8	39.4	85
	7712	149.0	114.2	11.4	60
	7710	215.0	586.0	5.7	51
	7708	156.0	324.0	6.5	86
	7707	185.0	158.8	9.9	93
2029C4	7703	234.0	88.0	15.0	70
	7701	236.0	76.2	18.6	62
	7699	177.0	91.2	9.0	79
	7697	158.0	115.6	11.6	75



MODEL PARAMETERS

Model Type		Tabular
Depth	F	13.6 m
Half Width	F	98.1 m
Dip	F	85 deg.
Susceptibility	X	0.000650 emu
Remnance Ratio	F	29.06239
Remnance Incl.	X	−59 deg.
Remnance Decl.	X	220 deg.

GEOMAGNETIC FIELD

Field Strength	31 000 nT
Inclination	−55 deg.
Declination	−1 0 deg.

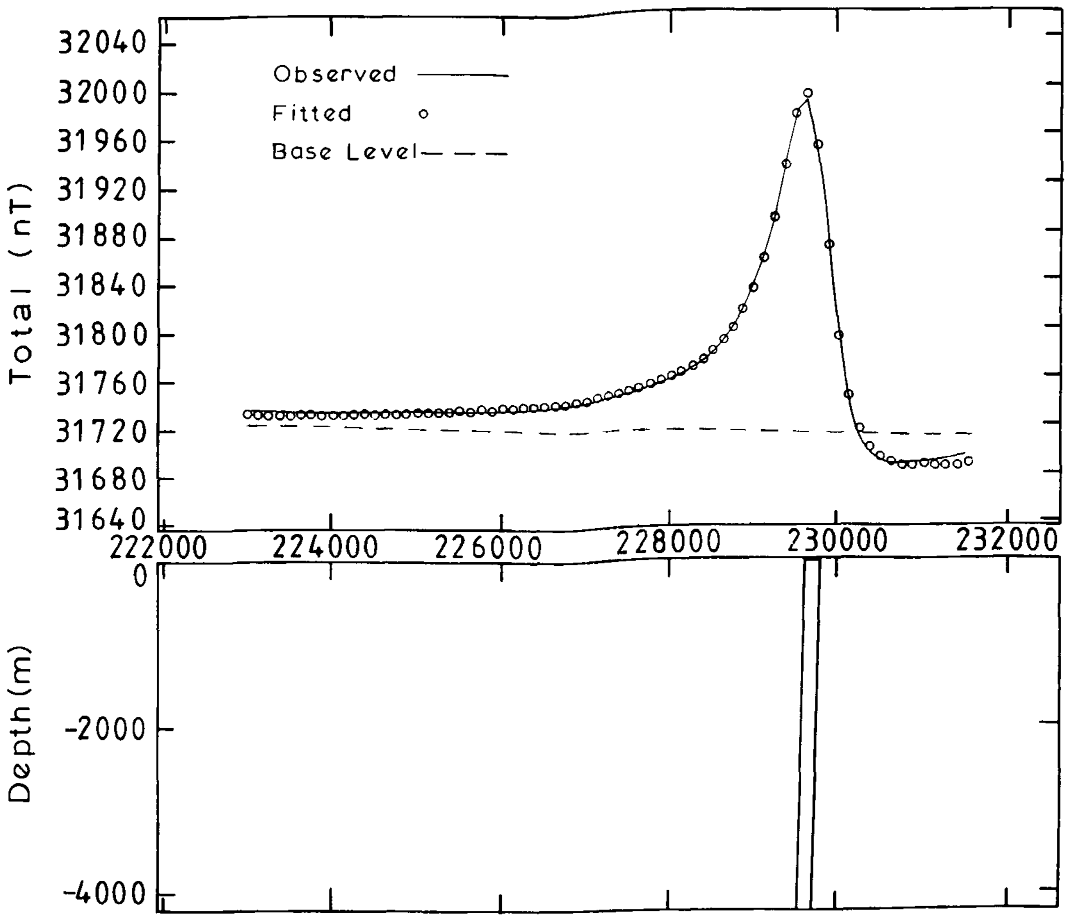
(F–fitted, X–fixed)

Fig. 2: Two typical profiles across the Umvimeela Dyke (location shown in Fig. 1), with the fitted model and the model parameters

Fig. 2 (cont)

1780C2

UTM LINE 8040000



MODEL PARAMETERS

Model Type		Tabular
Depth	F	28.7m
Half Width	F	86.0m
Dip	F	91 deg
Susceptibility	X	0.000650 emu
Remnance Ratio	F	18.6066
Remnance Incl.	X	-59 deg
Remnance Decl.	X	220 deg

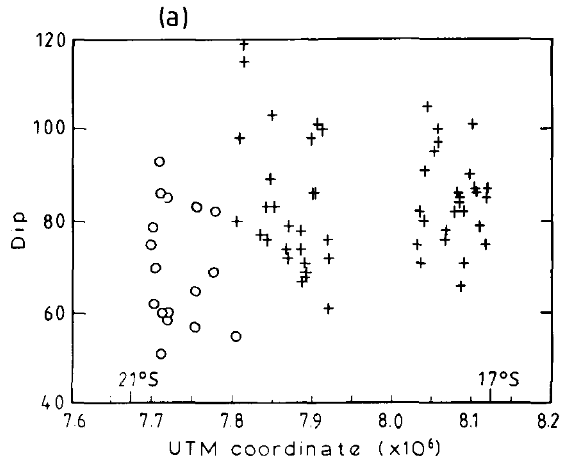
GEOMAGNETIC FIELD

Field Strength	31000 nT
Inclination	-55 deg
Declination	-10 deg

(F- fitted, X- fixed)

Table 2: Characteristics of the magnetic models of East Dyke

Topographic Map No.	UTM Line No. x103	Depth to Top (m)	Thickness (m)	Remanance Ratio	Dip
1730B4	8078	242.0	114.2	10.0	99
	8064	3.9	70.2	8.4	78
1730D1	8041	861.0	141.8	17.9	83
	8040	156.0	127.0	13.9	94
	8039	21.4	160.4	8.9	87
	8031	265.0	80.6	21.0	93
2030A1	7782	3.6	32.4	10.0	77
	7781	81.7	56.0	10.1	88
	7780	47.7	71.4	8.1	76
	7779	187.0	101.8	4.8	90
2030A3	7757	179.0	71.2	12.3	74
	7756	148.0	88.8	10.9	71
	7755	121.0	110.0	4.6	87



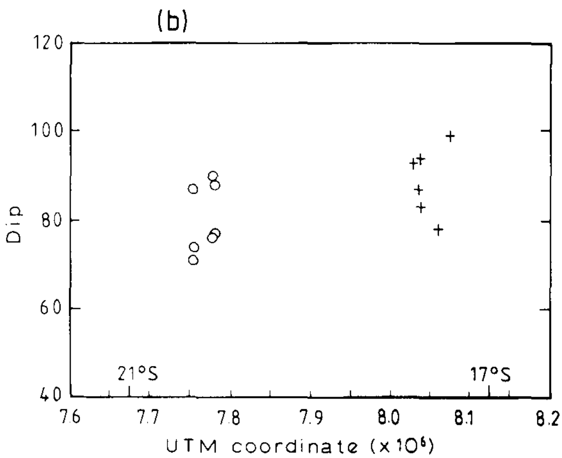


Fig. 3: Variation of dip with position (given by the UTM coordinate) for (a) the Umvimeela Dyke and (b) the East Dyke. Points south of coordinate 7 800 000 are plotted with a different symbol.

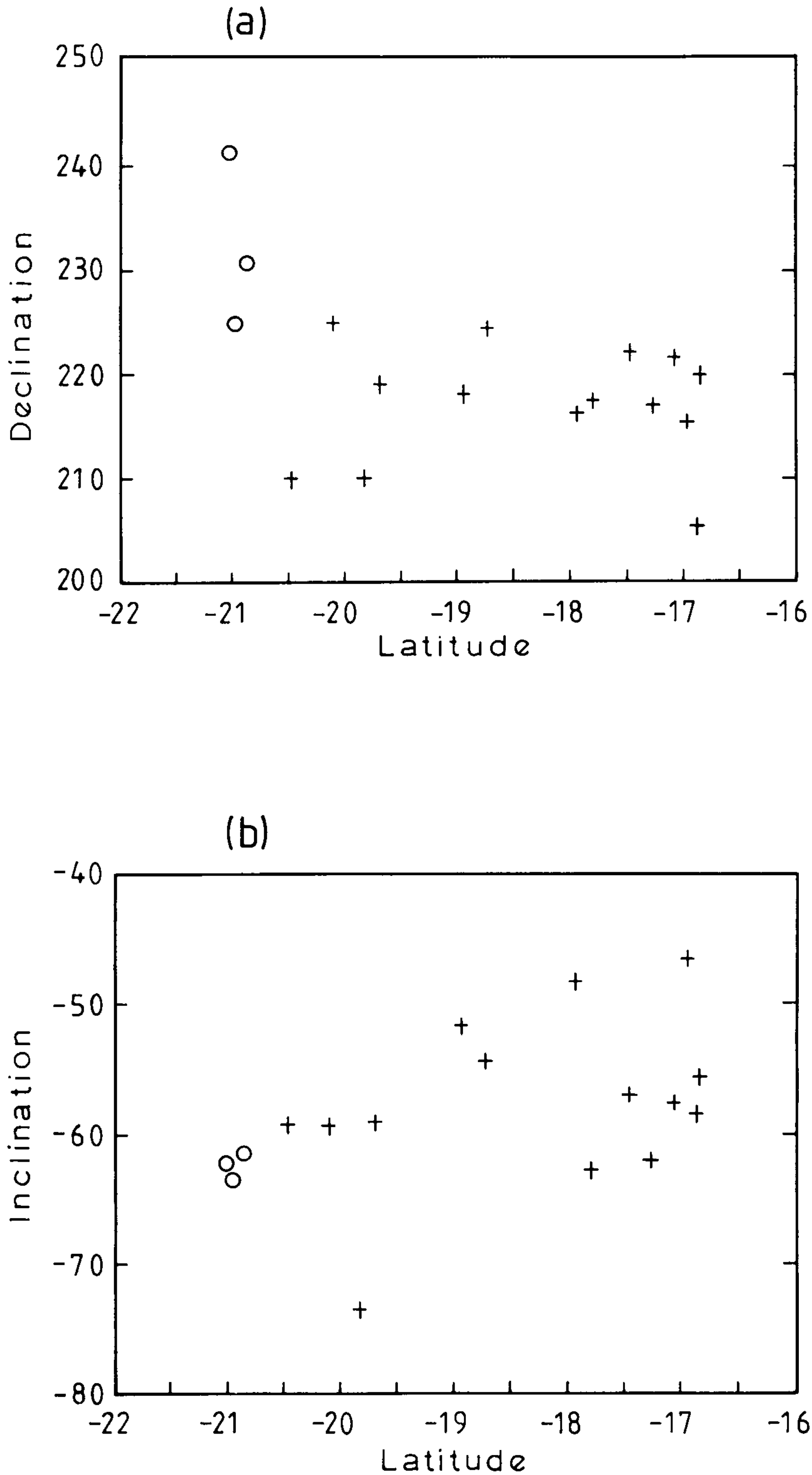


Fig. 4: Variation of the direction of the primary magnetization in the Umvimeela Dyke with latitude (Mushayandebvu, 1991). (a) gives the declination and (b) the inclination. Points south of latidue 20.5°S have been plotted with a different symbol.

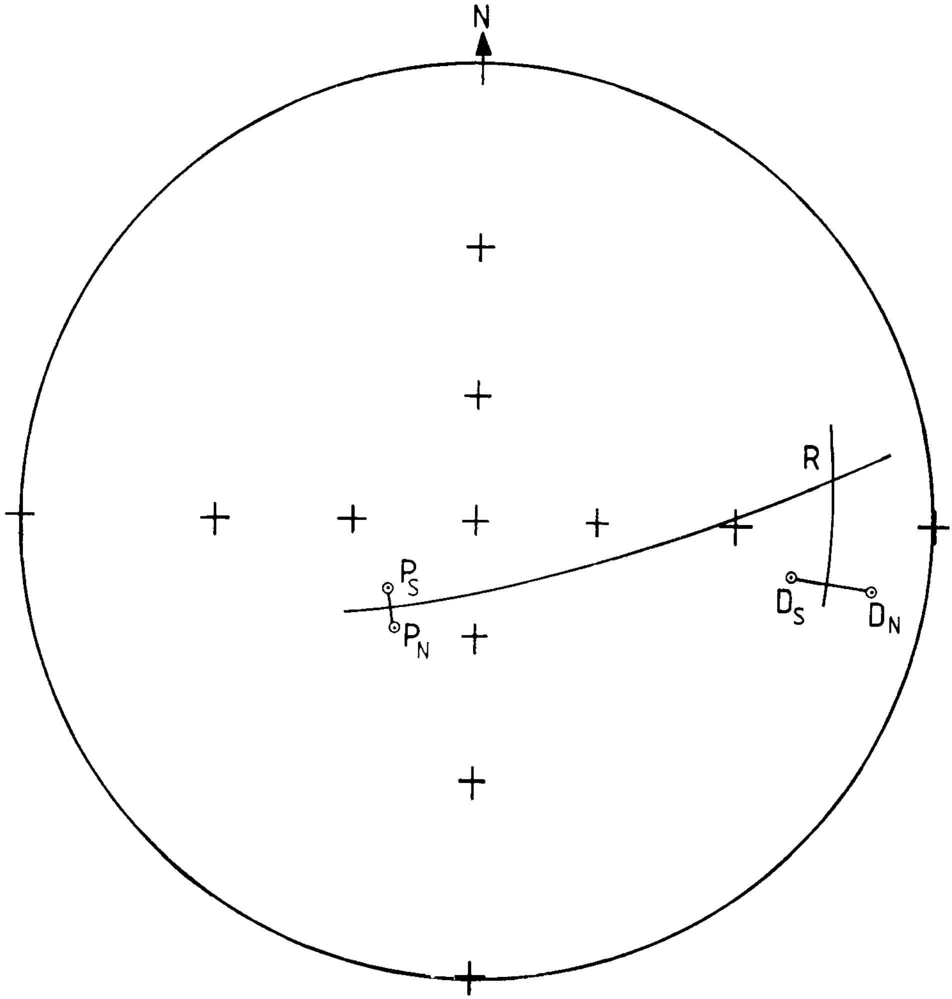


Fig. 5: Equal angle stereographic projection of the direction of the primary magnetization north (PN) and south (PS) of latitude 20.5°S and the direction of the normal to the dyke north (DN) and south (DS) of UTM coordinate 7 800 000. Point R, the intersection of the planes that bisect the angles between the two pairs of directions, represents the common rotation pole.

southern section results brings both dips and remanent magnetization into agreement with those to the north, this would support the rotation hypothesis.

The mean directions of magnetization P_N and P_S have been plotted on an equal angle stereonet (Fig. 5). The pole of rotation that would take P_S into P_N lies in the plane which is the normal bisector of the angle between P_S and P_N, as shown on Fig. 5. If the directions of dips of the dyke are represented by normals to the dyke, then the northern section has a declination of 100° with a mean dip of -6.1° while the southern section has the same declination with a mean dip of -19.9°. The two directions are now labelled D_N and D_S respectively. The tilt of the southern section that would bring D_S to D_N has a pole of rotation which lies in the plane which is the normal bisector of the angle between D_S and D_N. The two planes intersect at point R (Fig. 5) corresponding to a declination of 83° and an inclination of −12 . This represents the only pole of rotation that would take P_S to P_N and D_S to D_N, and the direction is roughly parallel to the northern margin of the Limpopo Belt. However, different magnitudes of rotation are required for the two data sets; the better defined palaeomagnetic directions require a rotation of about 10°.

The difference observed in dips and in the direction of the remanent magnetisation could be explained by a tilting of the region south of latitude 20.5°S and extending EW to include both the Umvimeela and the East dykes. The affected zone, if not limited by the cross-cutting Mchingwe Fault set, could be extended to represent a regional tilting of the Zimbabwe craton adjacent to the Limpopo Belt, over a zone about 100 km wide. The direction of the pole of rotation suggest a rotation/tilt as a result of Limpopo Belt activity.

A regional tilt of about 10° over a 100 km wide zone would imply a vertical difference of about 16 km between the edges of the zone. The tilt could either represent a block tilt or a limb of a gentle fold. No other sign of this difference in levels, either from stratigraphy or metamorphic grade has been previously reported. If the inferred rotation did occur it would have implications in the continent-continent collision models of the Limpopo Belt which have rocks of the Kaapvaal craton thrust onto the Zimbabwe craton.

Summary and conclusion

Models of the Umvimeela and East dykes of Zimbabwe have been deduced from aeromagnetic data. The models show the two dykes are essentially vertical north of latitude 20.5°S with a dip of 84° towards the Great Dyke for the Umvimeela dyke and 89° away from the Great Dyke for the East dyke. There is a lot of scatter in the dips. There is a large variation in the width of the dykes with the Umvimeela dyke giving a mean of 204 m and 106 m for the East dyke. The large errors may represent true variations in width or result from variations in the magnetic susceptibility. Both dykes have shallower dips south of latitude 20.5°S. The Umvimeela dyke dips at 70° and the East dyke at 80°. This, together with palaeomagnetic data from the Umvimeela dyke, suggests a tilting of the Zimbabwe craton adjacent to the Limpopo Belt of about 10° over a zone about 100 km in width. The direction of the rotation pole is roughly parallel to the northern margin of the Limpopo Belt with a declination of 83° and an inclination of −12° suggesting that the tilting is a result of Limpopo Belt activity.

The regional tilt would imply a vertical difference of about 16 km between the edges of the zone. No stratigraphic signs or changes in metamorphic grade have been reported to support the tilting. There is the possibility that the affected zone was limited by the cross-cutting Mchingwe Fault set. If the inferred rotation did occur it will have implications in the continent-continent collision models between the Zimbabwe and Kaapvaal plates of the tectonic history of the Limpopo Belt.

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